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COMBAT ENGINEER EFFECTIVENESS IN SUSTAINED OPERATIONS

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ABSTRACT

The effect of sleep deprivation and physical fatigue on self-paced work output was determined in two sustained combat engineer operations. In the first (Ripe Sapper), four subjects from 2 Combat Engineer Regiment went without sleep for 69 hours. During this period they performed only four physically demanding tasks, three of them in the last 24 hours. Continuous recordings of heart rate (HR) indicated that sleep deprivation, in the absence of physical fatigue, had no effect on work intensity and the work/recovery cycle. In the second sustained operation (Longue Journée), six subjects from 5 Combat Engineer Regiment carried out a full schedule of physically demanding tasks during a period of sleep deprivation lasting 47 hours. Some of the tasks were repeated at least once so that the effects of sleep loss and physical fatigue could be assessed. For the first 14 hours of Longue Journée, the subjects worked at an average HR of 120 bpm which is equivalent to an energy expenditure of 35-40% of maximal oxygen uptake in fit young men. In the remainder of the sustained operation, work intensity declined as the subjects worked for shorter periods and took longer rests. Rating scales confirmed that these changes coincided with the development of physical fatigue. Since sleep deprivation was without effect in Ripe Sapper, the decline in self-paced work output in Longue Journée was attributed to physical fatigue.

Although the evidence is not conclusive and must be confirmed by further research, the results of this study have important implications for those responsible for planning sustained combat engineer operations. Longue Journée demonstrated that the subjects, typical combat engineers, were able to complete all the tasks assigned to them within the allotted 48 hours. Although times to complete individual tasks increased in the later stages, the goal of operating continuously for 48 hours was achieved. The finding that sleep loss, per se, had no effect on self-paced work output in Ripe Sapper suggests that soldiers who are sleep deprived, but not physically fatigued, can be expected to complete physically demanding tasks in the same time as fresh troops. Moreover, troops who receive at least four hours of dedicated sleep every night should not be considered immune to the effects of sustained operations. If the 20 waking hours are spent in prolonged fatiguing tasks, self-paced work output may still decline.

INTRODUCTION

The Director of Military Engineer Plans (DMEP) tasked DCIEM to investigate the effect of sleep deprivation and physical fatigue on sustained combat engineer operations. As the first phase of this tasking, a review of the scientific literature was carried out (18) which indicated that there was no data directly related to combat engineers and little that was indirectly relevant. Most of the published work in sustained operations deals with the effect of sleep loss on mental performance during sedentary tasks (1,2,8). There have been recent studies of sustained infantry and artillery operations (14,28), but none of the data on work output is directly relevant to combat engineers. Studies of manual labour in civilian occupations are concerned with a working day no longer than eight hours (3,24,25,27). The review (18) did stress that the tasks performed by combat engineers will be essentially self-paced, dependent on subject motivation and therefore sensitive to sleep deprivation and/or physical fatigue.

Having identified the gaps in existing knowledge, the review (18) recommended research to answer the following questions.

1. What is the energy cost of typical combat engineer tasks?

2. Can these tasks be performed without sleep for periods up to 48 hours and at what physiological cost?

3. What is the effect of sustained operations on the work output (productivity) of combat engineers?

The first project was a field study (20) carried out at CFB Petawawa using subjects provided by 2 Combat Engineer Regiment (2 CER). For eight hours on four consecutive days, with adequate rest and sleep during the evening and night, these subjects performed three of the most physically demanding combat engineer tasks. These were abatis (blocking a road by felling trees), preparing a minefield, and cratering a road with explosives. Continuous recordings of heart rate (HR) showed that the work was intermittent, with periods of relatively intense exercise offset by rest or light activity. Average heart rates were below 120 bpm for all three tasks, indicating that the average energy expenditure was less than 35-40% of their VO_2max. The field study at CFB Petawawa confirmed the generally accepted view that this level of energy expenditure can be maintained by reasonably fit young men for eight hours without undue fatigue (17).

The next step was to extend the work period to at least 48 hours and this report contains data from two such experiments. The first made use of a sustained combat engineer operation with the codename Ripe Sapper, one of several carried out during the Rendez-Vous 85 (RV 85)

manoeuvres at Camp Wainwright in the Spring of 1985. In Ripe Sapper, the subjects were sleep deprived, but not physically fatigued. The second experiment, codenamed Longue Journée, was conducted at CFB Valcartier in the Fall of the same year. It was designed so that the subjects were exposed to physical fatigue as well as sleep loss. From a comparison of the self-paced work output in the two sustained operations, it would be possible to assess the separate effects of the two stressors.

METHODS

The Observer Team

The two sustained combat engineer operations, Ripe Sapper and Longue Journée, were monitored continuously by two teams of observers, each consisting of a combat engineer officer from NDHQ and scientists from DCIEM and DLOR. The teams worked 12 hour shifts to record in detail what each subject did, when he started work and when he stopped. These records were used to prepare the activity diaries presented in the General Observations Section for each sustained operation.

Although they were supervised by a Sergeant in both sustained operations, the subjects were allowed to work at their own pace in both experiments. They were familiar with the type of work assigned to them and were instructed to work as a team to complete each task and move on to the next one as soon as possible. By these criteria, the work in Ripe Sapper and Longue Journée can be considered self-paced and therefore susceptible to factors which affect subject motivation.

Assessment of Physical Fatigue and Sleepiness

Physical fatigue was assessed in Ripe Sapper using a fatigue checklist (9) which asks the subject to rate himself against a list of ten descriptive phrases (quite fresh, slightly pooped, etc.). He may indicate that he feels better than (2 pts), the same as (1 pt), or worse than (0 pt) each of the descriptors. Adding the points gives a fatigue score of 0 to 20, with zero indicating the most fatigued state possible. The times when the checklist was administered are indicated in the activity diary for Ripe Sapper.

Since the subjects in Longue Journée spoke only French and some of the descriptive phrases used in the checklist (9), such as "petered out", translated badly, it was decided to prepare a new and simpler rating scale for Longue Journée. In the new version, subjects were asked to make a mark on a 100 mm line whose left and right ends corresponded to the terms "pas du tout" and "trop fatigué". A similar rating scale was prepared for sleepiness which had the right end labelled "trop endormi". The times at which the two scales were administered are indicated in the activity diary for Longue Journée.

Although the need for different rating scales is unfortunate and could have been avoided by anticipating the problem with translation, the difference is not sufficient to invalidate the conclusions drawn later regarding the fatigue state of the subjects.

Continuous Recording of Heart Rate

Heart rates were recorded continuously by means of the personal monitoring system (PMS-8) manufactured by the VITALOG Corporation of Palo Alto, California. The PMS-8 is a small microcomputer worn on a belt at the waist and connected to three chest electrodes. Heart rate was measured every 10 sec and stored in solid state memory. After approximately 24 hours of continuous recording, the stored data were transferred to disc using an Apple IIe computer. An initial assessment of the PMS-8 as a means of collecting physiological data under field conditions is included in a previous report of this tasking (20).

At the end of the experiment, the data stored on disc were analyzed and presented in the following three formats.

1. Hourly Average Heart Rates

The average HR was calculated for each hour of elapsed time (from the start of the sustained operation). An hourly average is a reasonable measure of energy expenditure for work which is intermittent and involves a significant amount of arm or isometric exercise (4,24).

2. Work Intensity Based on Heart Rate

From the activity diary, time periods can be identified when the subjects are at rest, moving by vehicle or engaged in activities such as fence construction or road cratering. The HRs during these time periods were analyzed to show the percentage of time spent in each of three zones corresponsding to the classification of activity as rest or light work (less than 120 bpm), medium work (120-140 bpm) and heavy work (greater than 140 bpm) proposed by Christensen (6).

3. Work/Recovery Cycles

In a previous study (20), it was proposed that the VITALOG PMS-8 be used to monitor the work/recovery cycle for tasks where the work is intermittent. In this application, the work period (w) is arbitrarily defined as the time when the HR is at or above 120 bpm and recovery (r) as the time when HR is below this level. This HR was chosen because it represents an energy expenditure of 35-40% of their VO_2max for subjects of similar age and training state as the combat engineers tested in this study (30). Since it is assumed that prolonged work at HRs above 120 bpm will eventually cause fatigue, it may be more appropriate to describe the ratio w/r as a measure of the cycle of "fatiguing" work and recovery.

RIPE SAPPER - GENERAL OBSERVATIONS

Ripe Sapper was a sustained operation carried out by 2 CER as part of RV 85 at Camp Wainwright, Alberta, in May 1985. A Sergeant, a driver and four Sappers were assigned to DCIEM to act as subjects. In the experimental protocol, it was intended that these men would be assigned a sufficient number of tasks by the controller for Ripe Sapper, located at Regimental Headquarters, to keep them active and without sleep for at least 48 hours. Due to delays in obtaining supplies, problems with radio communications and excessive time spent travelling by vehicle, this did not happen. In the first half of Ripe Sapper, the subjects performed only one task, construction of a type 2 catwire wire fence; in the second half, they completed three road cratering tasks.

The following is an activity diary which summarizes the main events in Ripe Sapper. Date and time of day are indicated on the left with elapsed time (from the start of the sustained operation), in hours, shown in parentheses. Although the activity diary indicated that Ripe Sapper began at 1600, the subjects had been awake since morning and engaged in preparing for the official start. Estimates of accumulated sleep deprivation should add approximately nine hours to the elapsed time.

May 11

1600-1800	Briefing and preparation of the subjects, VITALOG equipment connected to the subjects, HR recording begins (2.00)
	Rating of physical fatigue recorded
1800-2200	Road move of 75 km by vehicle (6.00)
2200-2400	Arrive at final destination, move under camouflage cover, stay at this location waiting for supplies (dummy mines, rolls of barbed wire, pickets, etc.) (8.00)

May 12

0000-0500	Still at same location waiting for supplies (13.00)
0500-0630	Supplies arrive, load supplies, move to new location (14.50)
0630-1600	Deny a potential airstrip to the enemy by erecting a double picket fence, 600 m in length, with barbed wire in concertina rolls (type 2 catwire fence) (24.00)
	Rating of physical fatigue recorded

1600-1830 Load unused supplies, road move by vehicle, unload supplies in headquarters area (26.50)

1830-2100 Supper, move by vehicle to new location (29.00)

2100-2400 Reconnaissance of next work site by vehicle and on foot (32.00)

May 13

0000-0330 Movement by vehicle with frequent stops (35.50)

0330-0400 Loading explosives (36.00)

0400-0415 Short vehicle move to work site (36.25)

0415-0830 Preparation for road craters using camouflet tubes, main charges in place for demolition at a later time (see note on cratering at the end of the activity diary) (40.50)

0830-1000 Breakfast and vehicle move to next cratering site (42.00)

Rating of physical fatigue recorded

1000-1600 Preparation for road craters using camouflet tubes, main charges in place for demolition at a later time (48.00)

1600-1730 Supper and rest period (49.50)

1730-1830 Vehicle move to next cratering site (50.50)

Rating of physical fatigue recorded

1830-2200 Preparation of road craters using camouflet tubes, main charges in place for demolition at a later time (54.00)

2200-2330 Vehicle move to new location (55.50)

2330-2400 Loading mines from supply truck (56.00)

May 14

0000-0200 Vehicle move to a new location (58.00)

0200-0400 Reconnaissance by vehicle with frequent stops, confusion as to location for minefield, order received to cancel last task, troops ordered to go to ground (60.00)

0400 VITALOG equipment disconnected from subjects, HR recording terminated

Rating of physical fatigue recorded, accumulated sleep loss now 69 (60 + 9) hours

0430 Subjects allowed to sleep, charges detonated at all three cratering sites in daylight hours

Note on road cratering using camouflet tubes:

The first step in the road cratering task is to create nine cylindrical holes distributed across the width of the road, to take the main charges which, when detonated, produce the craters. At Camp Wainwright, the holes were formed using camouflet tubes and small explosive charges. Camouflet tubes are hollow steel pipes, about 2.5 m in length and 5 cm in diameter, which are driven vertically into the ground using a heavy (32 kg) hammer device which fits over the top of the tube. This device, called a "thumper" by combat engineers, has four handles and is raised and brought down forcibly on the top of the tube by four men working in unison. When the final depth is reached, the camouflet tube is withdrawn approximately 25 cm. This leaves a space into which the small charge is lowered through the hollow centre of the tube. The small charge is detonated creating a small chamber, the camouflet tube is withdrawn entirely and the main charge is packed into the small chamber. Detonation of the nine small charges is carried out simultaneously by means of interconnected detonation cord and a safety fuse, likewise for the nine main charges.

RIPE SAPPER - RESULTS

Heart rates were recorded continuously for 60 hours from the four Sappers. Since they worked together on tasks, their data were combined and are presented as the average values for four subjects.

Hourly Average Heart Rates

Figure 1 shows the hourly average HRs for the four subjects plotted against time. This graph indicates that the hourly average exceeded 120 bpm in only five of the 60 hours for which data were collected. Hourly average HRs slightly above 120 bpm occurred for two consecutive hours during the fence construction task. Hourly average HRs were above 120 bpm in the first two cratering tasks, but barely so during the third. At all other times, the hourly averages were below 120 bpm.

Work Intensity Based on Heart Rate

In the first 30 hours of Ripe Sapper, HRs were below 120 bpm except when loading supplies or during the fence construction task. When

loading dummy mines, rolls of wire and other items aboard a truck, HRs were above 120 bpm for only 12 % of the time and never above 140 bpm. During construction of the type 2 catwire fence, HRs were above 120 bpm for approximately half the time, but were above 140 bpm for only 5%.

In the second half of Ripe Sapper, three road cratering tasks were completed. In the type of cratering carried out in Ripe Sapper, the most physically demanding activity is hammering the camouflet tubes into the ground to prepare nine holes for the explosive charges. Other components of the task, such as preparing and placing explosives, can be considered light work. For the first two cratering tasks, the work intensity while hammering was relatively high, with HRs above 120 bpm for 92% and 82% of the time (Figure 2), and above 140 bpm for 55% and 46%, respectively. In the third cratering task, the observer team reported that the subjects appeared fatigued compared to the first two tasks. This difference was reflected in the work intensity for the third task; HRs for hammering were above 120 and 140 bpm for only 46% and 18% of the time.

Work/Recovery Cycles

The average duration of work (w) and recovery (r) for hammering the camouflet tubes in the three cratering tasks are shown in Table 1. Also indicated are the amounts of elapsed time, from the start of Ripe Sapper until the subjects began hammering, the ratio w/r and the average HR for the period (w + r). In the first and second cratering tasks, subjects worked for relatively long periods, took brief rests and the ratios w/r were 11.4 and 7.6, respectively. In the third cratering task, the work/recovery cycle reflected the signs of fatigue noted by the observer team. The duration of w and r were approximately equal and the ratio w/r was 0.9. Average HRs for (w + r) reflected the work/recovery cycle for all three cratering tasks.

Subjective Assessment of Physical Fatigue

The fatigue checklist was administered at intervals (see the activity diary) to the four working subjects (Table 2). Although physical fatigue appeared to increase with elapsed time, the scores must be interpreted in the light of previous experience with this particular checklist (19). For example, the initial value of 19.3 is high and may reflect the mood of anticipation and excitement apparent to the observer team at the start of the sustained operation. The next two values, taken during fence construction and before the second cratering task, are not indicative of fatigue. The fourth and fifth values, before the third cratering task and at the end of Ripe Sapper, are in the range normally reported for physically fatigued subjects (19).

No checklist or rating scale was administered to assess their sleepiness. Although they did obtain 1-2 hours of fitfull sleep during the first night, these subjects had been without proper sleep for 45 (36 + 9) hours by the time they began the first cratering task.

LONGUE JOURNÉE - GENERAL OBSERVATIONS

Longue Journée was a sustained operation carried out in the training area at CFB Valcartier, Quebec, by a Section from 5 Combat Engineer Regiment. The Section consisted of a Sergeant, a Master-Corporal, a driver and six Sappers. These subjects were dedicated to the scientific experiment and, as a result, there were none of the problems with supplies and communications that plagued Ripe Sapper. In Longue Journée, a full schedule of tasks was completed, consisting of road cratering (three times), abatis (twice), two 8 km marches, minelaying, the construction of a medium girder bridge and a type 2 catwire fence, and the preparation of individual defensive positions. Of the eleven tasks carried out during Longue Journée, six were completed in the first half. Three of the tasks in Longue Journée, cratering, abatis and the 8 km march, were repeated to allow a comparison of self-paced work output for the same task at different stages in the sustained operation.

The following is an activity diary which summarizes the main events in Exercise Longue Journée. Date and time of day are indicated on the left with elapsed time, in hours, shown in parentheses. The subjects were awake for approximately two hours before the official start time and this period should be added to estimates of accumulated sleep loss.

Sept 18

0715-0815	Briefing and preparation of the subjects, VITALOG equipment connected to the subjects, HR recording begins (1.00)
	Rating of physical fatigue and sleepiness recorded
0815-0850	Move by vehicle to first worksite (1.58)
0850-1115	Preparation for road craters by augering, placing of charges, detonation of charges (4.00)
1115-1210	Move by vehicle to next worksite (4.92)
1210-1240	Lunch (5.42)
1240-1340	Route denial by abatis (6.42)
1340-1355	Move by vehicle to next worksite (6.67)
1355-1900	Setting up defensive position by erecting a double picket fence, 400 m in length, with barbed wire in concertina rolls (type 2 catwire fence) (11.75)
	Rating of physical fatigue and sleepiness recorded

1900-1930	Dinner (12.25)
1930-2015	8 km march (13.00)
2015-2100	Rest period with snack (13.75)
2100-2400	Building a Medium Girder Bridge (16.75)

Sept 19

0000-0030	Finish building the Medium Girder Bridge (17.25)
0030-0140	Snack, move by vehicle to next worksite (18.42)
0140-0520	Preparation of minefield, 400 mines laved in six rows (22.08)
0520-0740	Move by vehicle back to HQ area, transfer data from VITALOG to disc and reprogram, shower and breakfast (22.42)
	Rating of physical fatigue and sleepiness recorded
0740-0800	Move by vehicle to next worksite (24.75)
	Rating of physical fatigue and sleepiness recorded
0800-1200	Preparation of road craters by augering, placing of charges, detonation of charges (28.75)
1200-1250	Lunch, move by vehicle to next worksite (29.58)
1250-1420	Route denial by abatis (31.08)
	Rating of physical fatigue and sleepiness recorded
1420-1440	Move by vehicle to next worksite (31.42)
1440-1945	Establishing individual defensive positions by digging trenches, laying a low-wire entanglement and mines (36.50)
1945-2015	Dinner (37.00)
	Rating of physical fatigue and sleepiness recorded
2015-2145	8 km march (38.50)
2145-2300	Snack, move by vehicle to next worksite (39.75)
2300-2400	Preparation of road craters using camouflet tubes (40.75)

Sept 20

0000-0040	Completion of road cratering task (41.42)
0040-0130	Snack, move by vehicle to minefield (42.25)
0130-0230	Retrieving mines, loading mines onto a truck (43.25)
0230-0300	Rest period, move by vehicle to last worksite (43.75)
	Rating of physical fatigue and sleepiness recorded
0300-0335	Preparation for road craters by augering (44.33)
0335-0400	Return to HQ area by vehicle, VITALOG equipment disconnected from subjects, HR recording terminated (44.75)
	Rating of physical fatigue and sleepiness recorded
	Accumulated sleep loss 46.75 (44.75 + 2) hours

Notes

1. In the road cratering task, the nine cylindrical holes for the main charges were formed by spade and auger. In Exercise Rine Sapper these holes were formed using camouflet tubes and small charges.

2 The minefield was created by marking out an area with pickets and barbed wire. Inside this area, dummy mines were buried just below the surface in staggered rows about 8 m apart.

3. In abatis, approximately 200 m of dirt road was blocked by trees from either side felled at an angle using chainsaws.

LONGUE JOURNÉE - RESULTS

Heart rates were recorded continuously for 44.75 hours from the six Sappers who worked together as a team. Their data were combined and are presented as the averages for six subjects.

Hourly Average Heart Rates

The hourly average HRs for the six working subjects are plotted against time in Figure 3. In six of the first 14 hours, the hourly average was above 120 bpm, indicating moderate to heavy work (6). These elevated HRs corresponded to the first abatis, 8 km march and cratering task. Although these and other physically demanding tasks were performed throughout the remaining 31 hours, the hourly average HRs never rose above 120 bpm again.

Work Intensity Based on Heart Rate

The experimental design for Longue Journée required that three tasks be performed at least twice. These were cratering (three times), abatis (twice) and the 8 km march (twice). On each occasion, the task was carried out in a similar location so that heart rate and time for completion could be compared. Heart rates recorded during these tasks were analyzed to show the percentage of time spent in each of three zones corresponding to light, moderate and heavy work (6).

The most physically demanding component of the three cratering tasks in Longue Journée was the preparation of nine holes for the explosives (see methods). Figure 4 shows the intensity levels for digging with spade and auger. Heart rates were above 120 bpm for 80% of the time in the first task, for 56% in the second and for 43% in the third. Heart rates were above 140 bpm for 44%, 16% and 12% of the time. Time required to complete the nine holes was 25, 31 and 32 min, respectively.

For the two abatis tasks (Figure 5), HRs were above 120 bpm for 67% and 33% of the time and above 140 bpm for 38% and 10%; times for completion of the task were 46 and 81 min, respectively.

The subjects chose to alternate walking and running for the first 8 km march, but to walk during the second. The difference is reflected in the HRs (Figure 6) which were above 120 bpm for 97% and 11% of the time and above 140 bpm for 85% and 5%; times to complete the distance were 47 and 93 min, respectively.

Work/Recovery Cycles

Work (w) and recovery (r) periods were calculated for the two abatis tasks and for digging the nine holes by spade and auger in the three cratering tasks (Table 3). In the first half of Longue Journée, w was 2-4 times as long as r and the average HRs were above 120 bpm. In the second 24 hours, a decrease in w was accompanied by an increase in r. As a result, w/r declined to values less than 1.0 and average HRs for the period (w + r) were below 120 bpm. Since marching tends to be a continuous activity, compared to cratering and abatis which are intermittent, work/recovery cycles were not calculated for the two 8 km marches. The decline in work intensity is best expressed by the average HRs which were 168 ± 8 and 111 ± 5 bpm for the first and second marches, respectively.

Subjective Assessment of Physical Fatigue and Sleepiness

The physical fatigue and sleepiness rating scales were administered at intervals (see the activity diary) to the six working Sappers. Figure 7 shows a steep increase in physical fatigue and sleepiness in the first 24 hours and a virtual plateau for both parameters in the second half.

GENERAL DISCUSSION

It is well established that sleep deprivation has a detrimental effect on mood and mental performance and that this decrement is least in tasks where the subject is interested and motivated (13,31). Boring mental tasks, where the subjects work at their own pace, can be expected to take longer to complete as the period without sleep increases. On the other hand, the physiological systems which determine the capacity for muscular exercise appear to be relatively unaffected by periods of sleep deprivation up to 65 hours (7,12,22,23,29). As a result, exercise which is paced by external cues, such as submaximal treadmill walking, is probably immune to sleep loss. This point is illustrated by data from a previous study originating from this laboratory (19) in which subjects walked at 28% of their VO_2max, one hour in three, for 64 hours without sleep. Table 4 shows that, although ratings of perceived exertion (RPE) by the Borg scale (5), increased progressively, oxygen consumption and HR were unchanged.

In sustained combat engineer operations, the work performed is essentially self-paced and sleep deprivation is often accompanied by physical fatigue. Since self-paced work depends on the interest and motivation of the subject, it is reasonable to suppose that work output (productivity) might be sensitive to changes in mood induced by sleep loss and physical fatigue. The objective of the present study was to test this hypothesis and to assess the separate effects of the two stressors.

Achieving this objective became a possibility when Ripe Sapper turned out to be less physically demanding than is normal for sustained combat engineer operations. The subjects completed only one major task (fence construction) in the first 30 hours and, except for two hours during this task, had hourly average HRs that were typical of sedentary activity (Figure 1). Since Ripe Sapper provided the opportunity to determine the effect of sleep deprivation alone, Longue Journée was designed so that the subjects became physically fatigued as well as sleep deprived. Eleven major tasks were carried out and six of these were completed in the first 24 hours. Hourly average HRs (Figure 3) confirmed that the energy expenditure was relatively high in the first 24 hours, but declined in the second half.

Sleep deprivation alone appeared to have no adverse effect on work intensity levels (Figure 2) and the work/recovery cycles (Table 1) for the first two cratering tasks in Ripe Sapper. The evidence for this statement is that the data obtained were quite similar to those for tasks performed in the first 24 hours of Longue Journée, by subjects who were not yet sleep deprived. Although the subjects in Longue Journée were assigned a full schedule of tasks in the second half, work intensity declined (Figures 4, 5 and 6). The work/recovery cycles (Table 3) suggest that the subjects worked for shorter periods and took longer rests in the second half of Longue Journée. Since sleep deprivation was

without effect in Ripe Sapper, the decline in work intensity and the changes in work/recovery observed in Longue Journée must have been due to some other factor.

If th decline in self-paced work output observed in the second half of Longue Journée was not due to sleep loss, then it may have been caused by physical fatigue. In Ripe Sapper, the rating scales support the reports of the observer team, that the subjects were not fatigued until just before the third cratering task. In Longue Journée, physical fatigue was fully developed by the end of the first 24 hours (Figure 7). Work intensity and the work/recovery ratio declined for the third cratering task in Ripe Sapper compared to the first two, but were similar to the data for tasks performed in the second half of Longue Journée. The coincidence between the development of physical fatigue and the decline in self-paced work output strongly suggests cause and effect.

Although the exact cause remains uncertain, it is clear that self-paced work output will decline from initial levels in a typical sustained combat engineer operation. In Longue Journée, the subjects worked relatively hard for the first 14 hours with an average HR of 120 bpm (calculated from the data in Figure 3). This value is comparable to the average HRs for abatis, minelaying and cratering performed for 8 hours daily by subjects who were neither sleep deprived nor physically fatigued (20). As Longue Journée progressed, work output declined and the average HR for the last 30 hours was 102 bpm (from Figure 3). A HR of 120 bpm represents an energy expenditure of 35-40% of their VO_2max for fit young men such as the combat engineers who served as subjects in the present study. It is generally accepted that, in the absence of heat stress or dehydration, work such as cratering or abatis can be performed at a HR of 120 bpm for 8 hours without undue fatigue (17). Lactic acid will not accumulate and muscular activity can be sustained by ingested food and adipose tissue stores. The experience of Longue Journée suggests, however, that this level of energy expenditure can be maintained for longer than 8 hours, perhaps for 12-16 hours, before physical fatigue causes a reduction to a lower but more sustainable level.

Implications for Sustained Combat Engineer Operations

Of the three questions posed in the Introduction, the previous discussion has provided answers to numbers one and three. Question two asks whether combat engineer tasks can be performed without sleep and at what physiological cost (strain). In answer to the first part, Longue Journée demonstrated that the subjects, typical combat engineers, were able to complete all the tasks assigned to them within the allotted 48 hours. Although times to complete individual tasks increased in the later stages, the goal of operating continuously for 48 hours was achieved. The second part of the question assumed two possible scenarios for Longue Journée. In one, the subjects would maintain a constant work output in the face of accumulating fatigue; an increase in HR would

therefore represent an increase in physiological strain (16). In the other scenario, work output would decline in response to an increase in fatigue; a proportional decrease in HR would suggest that there had been no increase in physiological strain (16). The data from Longue Journée conform to the latter scenario and it is concluded that the subjects decreased their work output as a means of maintaining or reducing physiological cost.

The data from Ripe Sapper and Longue Journée have other important implications for DMEP, the sponsor for this tasking. For example, it is clear that assigned tasks will take longer to complete in the later stages of a typical sustained combat engineer operation. During the three cratering tasks in Longue Journée, time to prepare nine holes for the explosives by augering took 25, 31 and 32 min. A more dramatic decline was evident for abatis, where times to complete the first and second tasks were 46 and 81 min, and for the 8 km march, where times were 47 and 93 min, respectively. This requirement for additional time should be taken into account by the sponsor when planning sustained operations.

Another finding with important implications is that sleep deprivation, per se, does not appear to cause a decline in self-paced work output. This observation is consistent with reports that sleep loss has no effect on perceived exertion (19,21) or walking speed on a "self-paced" treadmill (15,26). It means that combat engineers who are sleep deprived, but not physically fatigued, can be expected to complete physically demanding tasks in the same time as fresh troops. This situation could arise if units are obliged to travel long distance to the battle zone and must engage the enemy without time for recovery sleep. A proviso should therefore be attached to the generally accepted rule that four hours of dedicated sleep every 24 hours is adequate to maintain performance in sustained operations for up to 10 days (10,11). The proviso will stipulate that this rule is only true if the 20 hours of waking time is not spent in prolonged physically demanding work. Even with fours hours of sleep every 24 hours, physical fatigue could still cause a decrease in self-paced work output and may impair other aspects of performance.

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Table 1: Work (w)/recovery (r) cycles for cratering in Ripe Sapper.

Task	Elapsed time (hours)	w (min)	r (min)	w/r	Average heart rate (beats min^{-1})
Cratering					
1	36.2	4.45 ± 3.0	0.43 ± 0.1	11.4	147 ± 12
2	42.1	3.49 ± 3.1	0.54 ± 0.4	7.6	144 ± 14
3	50.4	1.04 ± 0.3	1.18 ± 0.4	0.9	123 ± 12

Values are means ± SD for four subjects preparing nine holes using camouflet tubes.

Table 2: Ratings of physical fatigue in Ripe Sapper.

Elapsed time (hours)	0	22.0	42.0	51.0	60.0
Fatigue score	19.3	13.5	13.0	8.5	9.0

Fatigue scores are means for four subjects.

Table 3: Work (w)/recovery (r) cycles for cratering and abatis in Longue Journée.

Task	Elapsed time (hours)	w (min)	r (min)	w/r	Average heart rate (beats min^{-1})
Cratering					
1	1.4	3.00 ± 1.4	0.78 ± 0.3	3.9	133 ± 8
2	24.6	2.53 ± 1.3	0.93 ± 0.2	2.7	122 ± 6
3	43.5	1.20 ± 0.4	1.57 ± 0.5	0.8	116 ± 7
Abatis					
1	5.3	3.90 ± 1.6	1.67 ± 0.7	2.3	133 ± 8
2	29.4	2.21 ± 1.4	3.93 ± 1.5	0.6	114 ± 6

Values are means ± SD for six subjects digging nine holes with spade and auger.

Table 4: Metabolic and psychophysical responses to sleep deprivation and chronic exercise

Response	Duration of sleep deprivation (hours)				
	0 - 12	12 - 24	24 - 36	38 - 48	48 - 60
Oxygen Consumption (L/min)	1.03 ± 0.02	1.02 ± 0.03	1.02 ± 0.03	1.06 ± 0.02	1.04 ± 0.03
Heart rate (bpm)	101 ± 2	100 ± 1	100 ± 1	100 ± 1	100 ± 1
RPE	8.7 ± 0.2	9.9 ± 0.2	10.5 ± 0.2	11.0 ± 0.2	11.2 ± 0.2

Values, means ± SD, for 12 subjects.
Data were taken from a previous study (19).

KEY TO FIGURES 1 AND 3

Number in Parenthesis	Major Task
1	Abatis
2	Preparing a minefield
3	Road cratering
4	Constructing a type 2 catwire fence
5	Constructing a medium girder bridge
6	An 8 km march
7	Preparing individual defensive positions

Figure 1

Hourly Average Heart Rates for Ripe Sapper

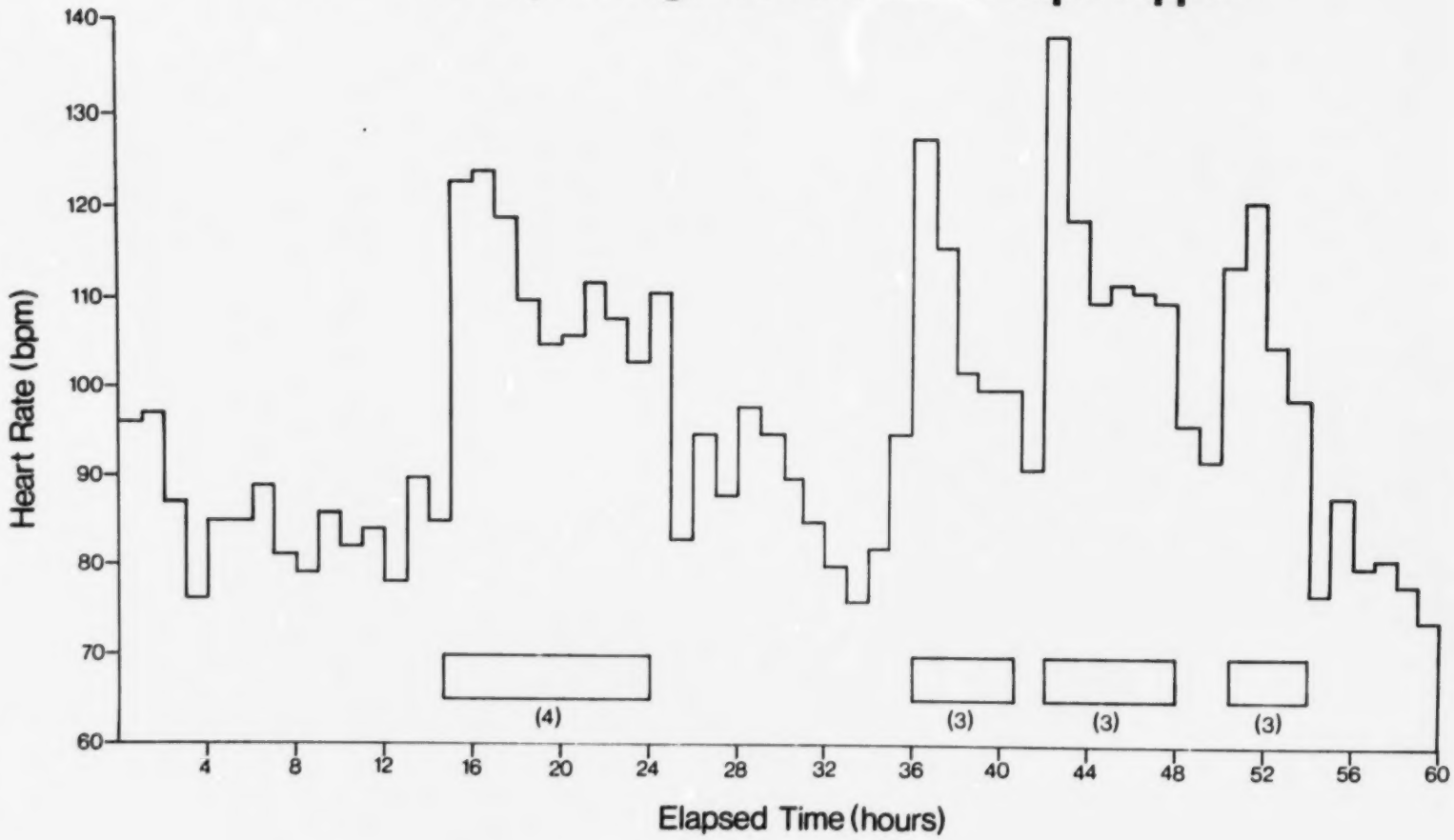

Figure 2. Work intensity for hammering camouflet tubes (cratering).

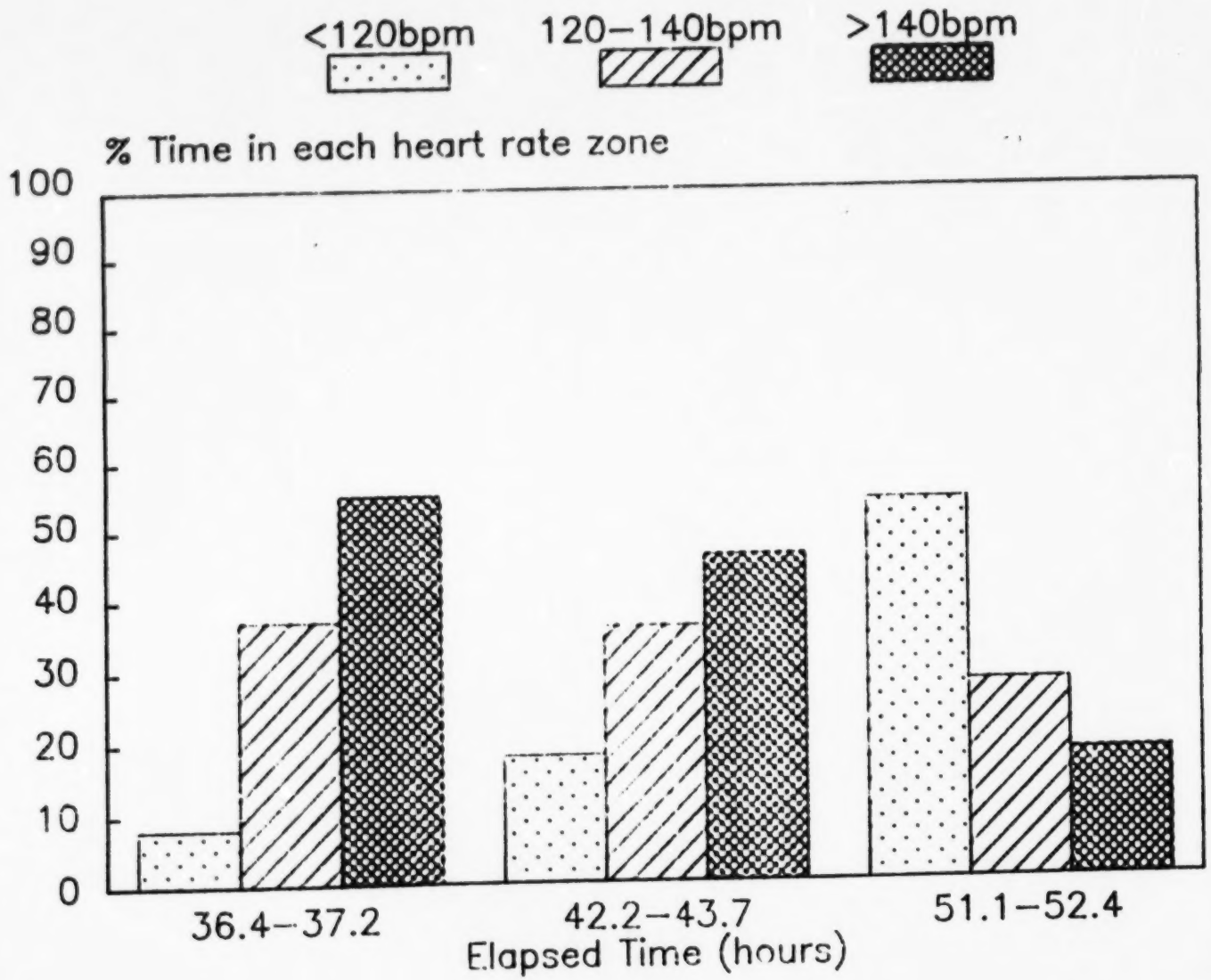

Figure 3

Hourly Average Heart Rates for Longue Journée

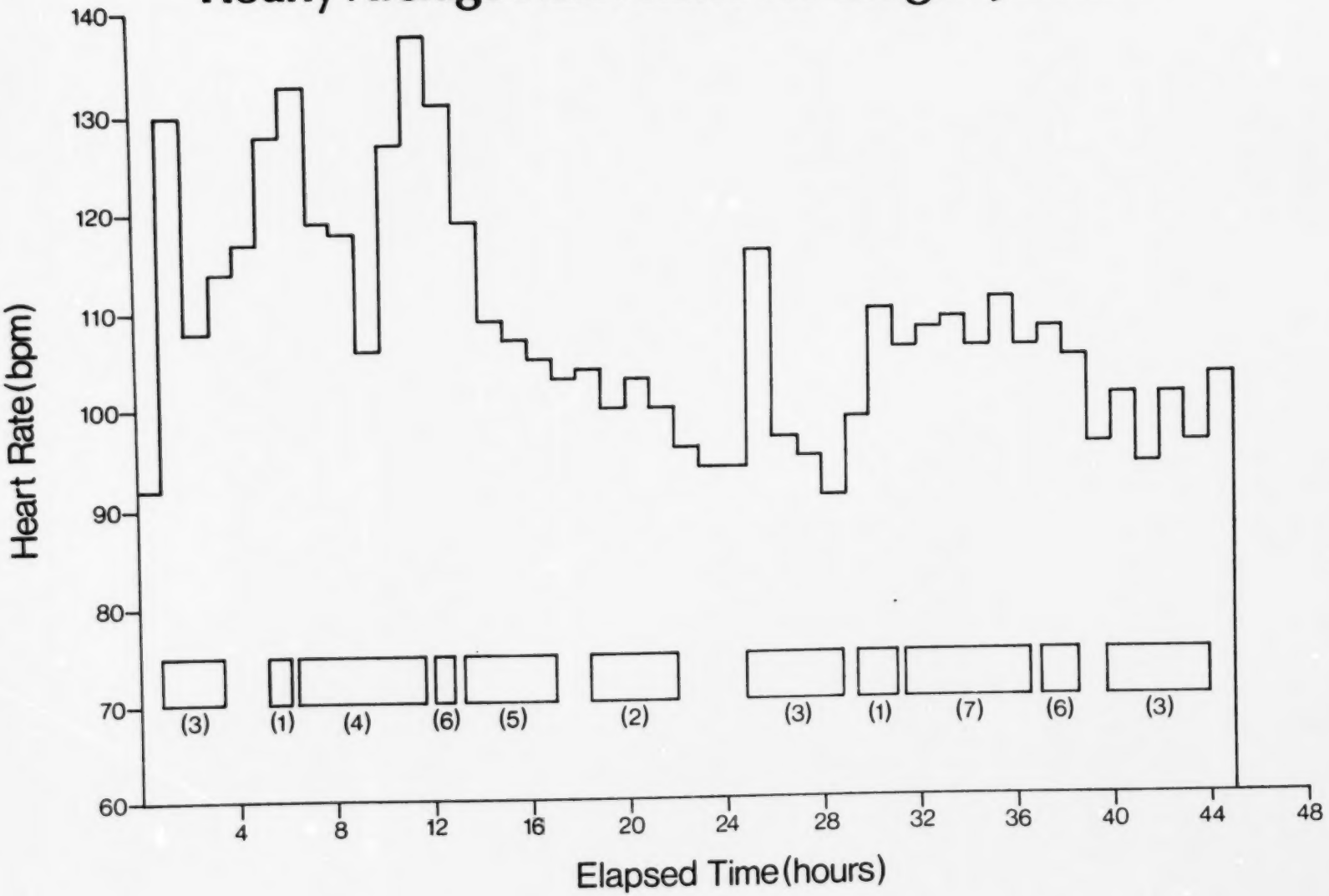

Figure 4. Work intensity for digging by spade and auger (cratering).

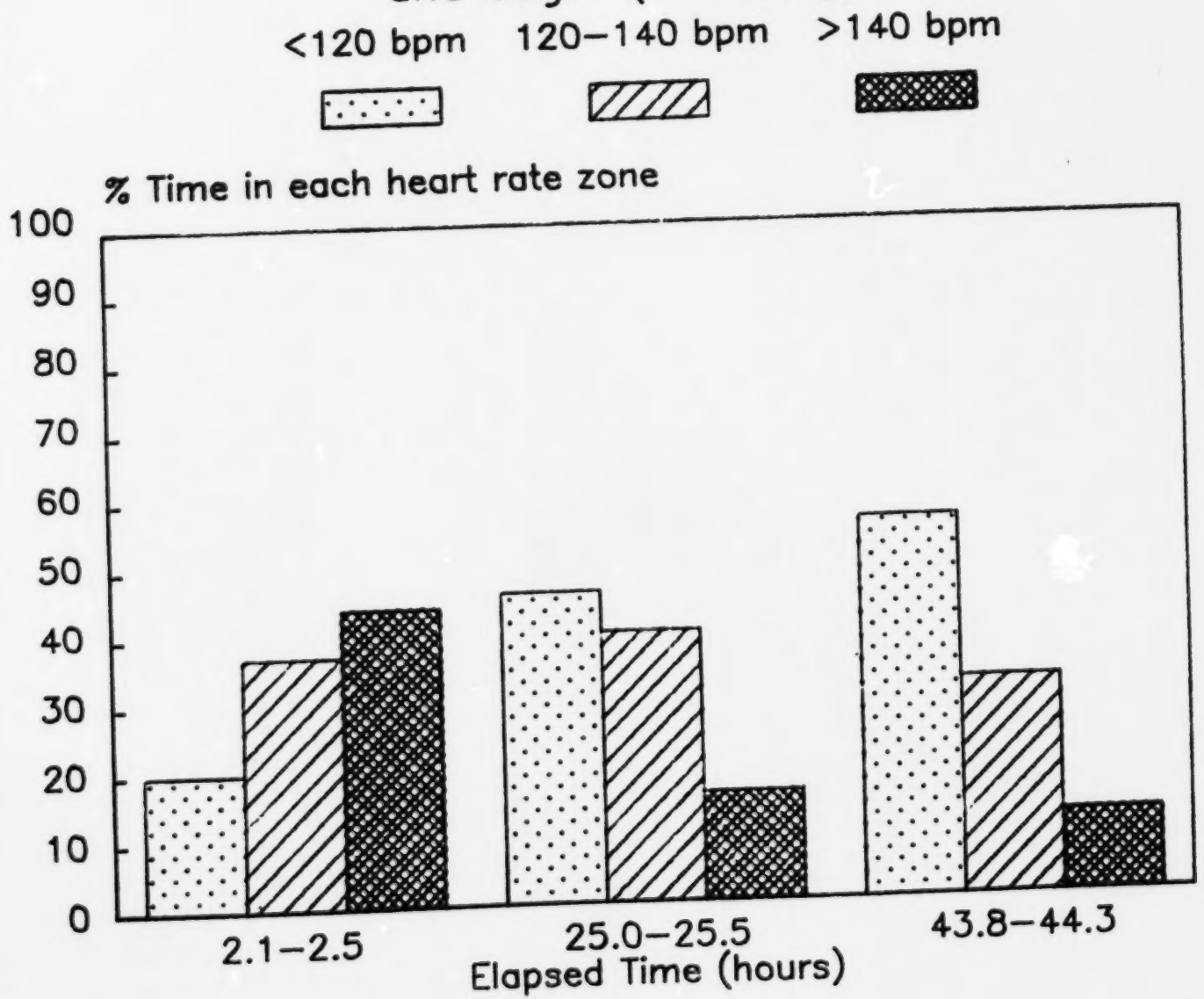

Figure 5. Work intensity for abatis.

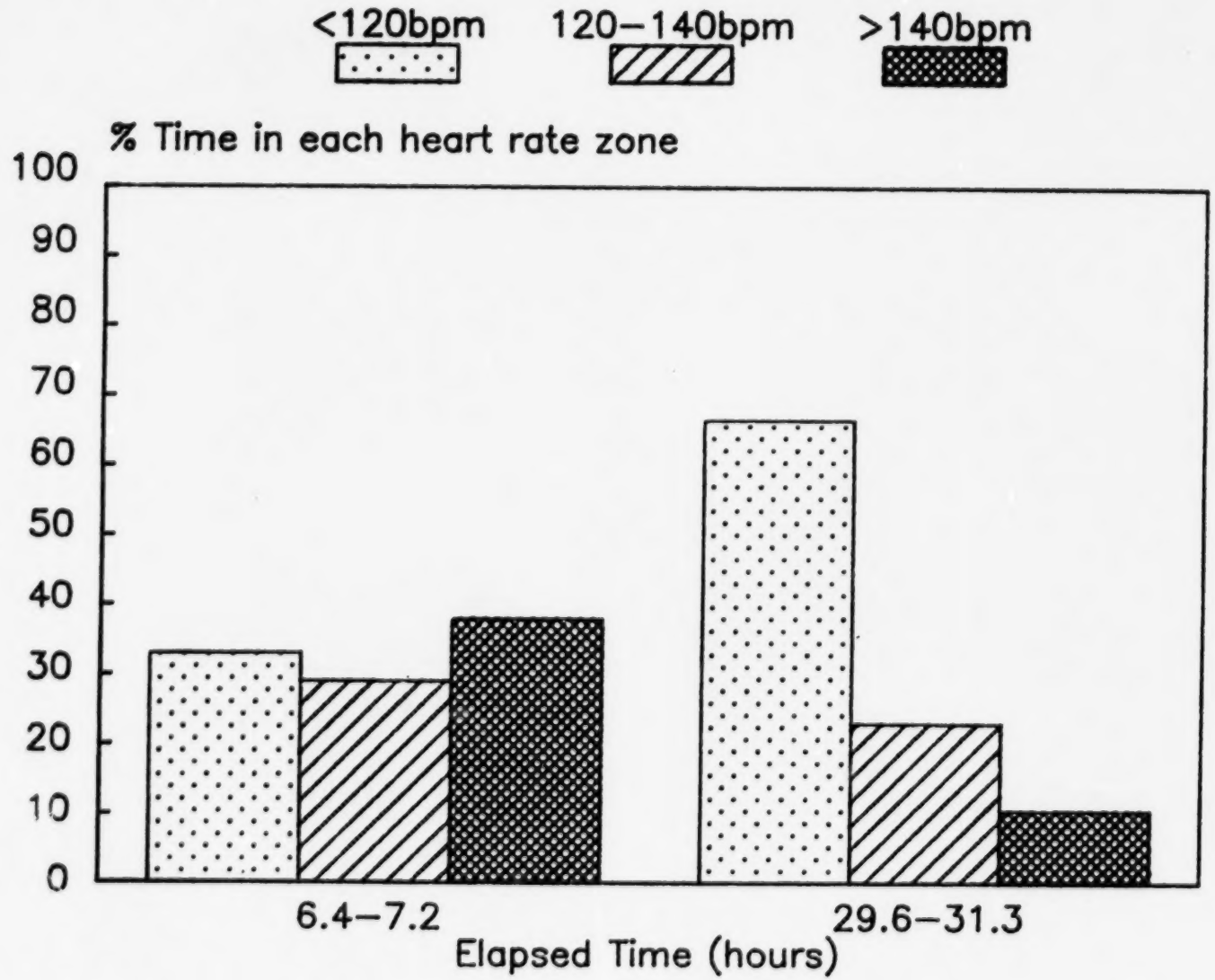

Figure 6. Work intensity for the 8 km march.

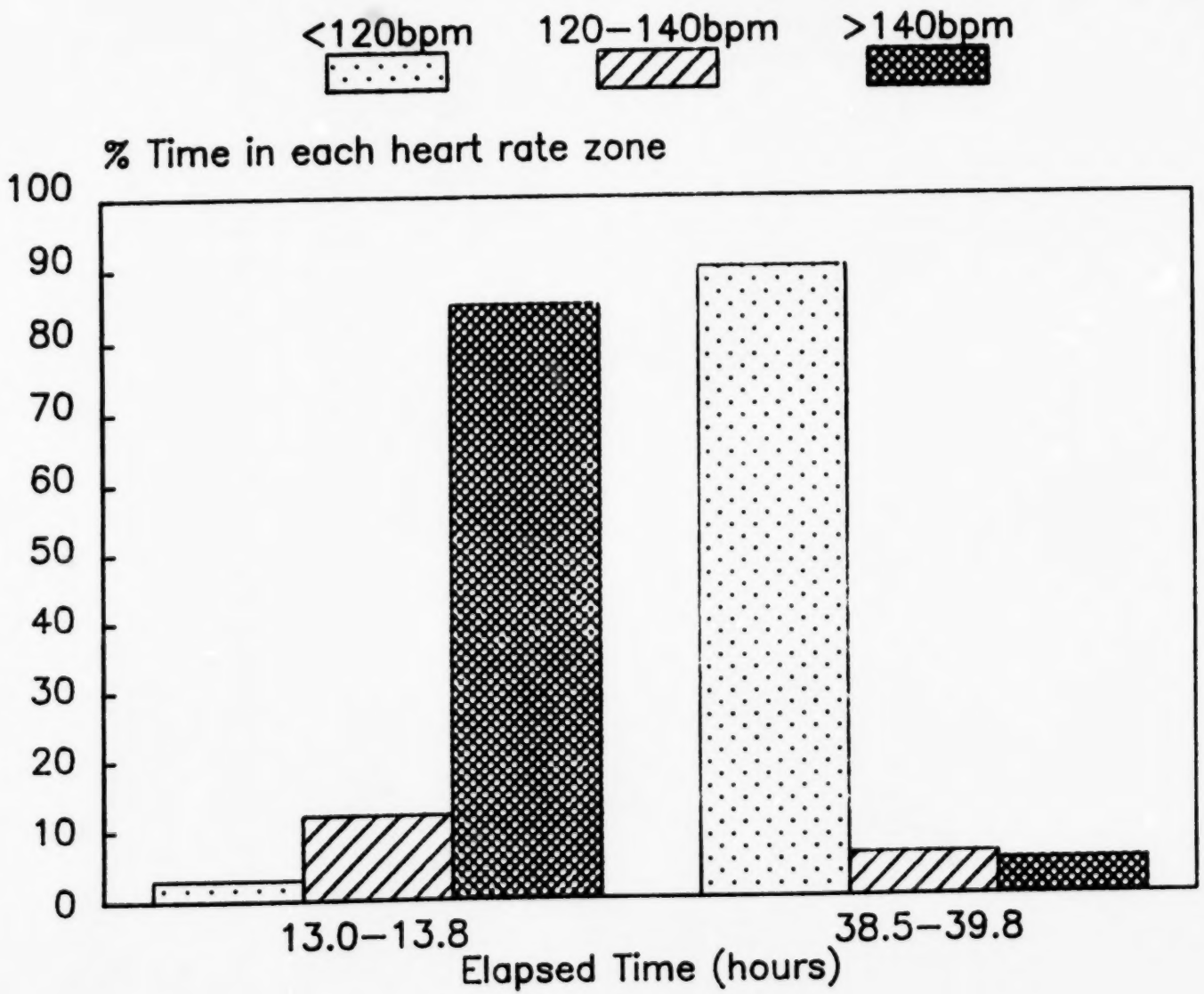

Figure 7. Physical fatigue and sleepiness during Longue Journée.